PROFILED BLADES FOR TURBOCHARGER TURBINES, COMPRESSORS, AND THE LIKE

FIELD OF THE INVENTION

The present invention relates generally to rotary apparatuses such as turbines and compressors that circulate a gas in a turbocharger and, more particularly, to an apparatus with a rotor having blades that define a nonlinear profile along at least one edge.

BACKGROUND OF THE INVENTION

Radial turbines and compressors, such as those used in turbochargers, typically include a rotor, or wheel, that is rotatably mounted in a housing and that defines blades extending radially outward in proximity to an inner surface of the housing. The housing defines an inlet for receiving air or other gas, and an outlet through which the gas is circulated. In the case of a turbine, the rotor is a turbine wheel that is rotatably mounted in a turbine wheel housing. Gas, such as exhaust gas from an internal combustion engine, flows into the housing through the inlet, which extends circumferentially around the wheel, and exits in a generally axial direction. As the gas passes through the housing, the turbine wheel is rotated. In a typical turbocharger, the turbine wheel is connected by a shaft to a compressor wheel, i.e., a rotor, that is rotatably mounted in a compressor wheel housing.

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The compressor wheel housing also defines an inlet and outlet, and the compressor wheel includes radial blades that deliver air through the compressor wheel housing. In particular, the compressor wheel draws air axially inward through the inlet and delivers the air radially outward through a diffuser that extends circumferentially around the compressor wheel.

The blades of the rotors of turbines and compressors typically have edges that are positioned in close proximity to the housing and other relatively stationary components. For example, the turbines and compressors of modern turbochargers can include stators at the inlet and/or outlet to control the flow of gas through the device. In a turbine, the stators can be vanes arranged circumferentially at the inlet to define a stationary or an adjustable nozzle. The nozzle can be selectively opened and closed to control the flow of the gas through the turbine. In a compressor, the stators can be vanes that are arranged circumferentially at the outlet to define a variable diffuser that controls the flow of the air through the compressor. Due to the close proximity of the rotors and stators, the high rotational speeds of the rotors, and the high operating pressures, the blades of the rotors are subject to unsteady aerodynamic excitation forces that induce alternating strains and stresses in the blades. Such unsteady, or cyclic, excitation forces can similarly result from other stationary or adjustable components such as inlet guide vanes or a curved inlet manifold that supplies the gas to the inlet at pressures that vary across the area of the inlet. For example, inlet guide vanes are often provided in the inlet of a compressor to direct the flow of air therethrough. Thus, the blades are cyclically stressed at frequencies associated with the rotational speed of the rotor and the number and location of the vanes or other stationary components. Such cyclic stress can result in fatigue and failure of the rotors.

A forced response analysis can be conducted during the design of a rotary device such as a turbine or compressor to determine the cyclic stresses and strains

on the rotor due to any unsteady aerodynamic excitation forces that occur at the rotor's resonant frequencies. The unsteady aerodynamic mechanical response of the rotor can be first analyzed, e.g., by conducting a computational fluid dynamics (CFD) analysis to determine the unsteady aerodynamic excitation forces, and conducting a 3-dimensional finite element method (FEM) analysis to determine the natural resonant frequencies of the rotor. Typically, the geometric configuration of the rotor or other components of the device is adjusted or modified as is practical to reduce the stresses and strains of the rotor that result from the unsteady aerodynamic excitation forces, e.g., by adjusting the configuration of the rotor or other devices such that the resonant frequencies occur outside the operating range of the rotor. The normal operating range of the device may be such that the rotor is not significantly stressed when subjected to cyclic aerodynamic forces that correspond to the lowest of the resonant frequencies of the rotor due to the low speed and pressure associated with that speed of operation. However, it is often impossible or impractical to adjust the higher resonant frequencies out of the operating speed range of the turbocharger. Thus, for example, the rotor may be subjected during some times of operation to a cyclic aerodynamic excitation force having a frequency that is equal to the second mode or higher modes of the resonant vibratory frequency of the rotor. Accordingly, the design analysis can include determining the strains and stresses that occur in the rotor at such frequencies and verifying that the expected life of the rotor meets a minimum design criteria. In some cases, however, the rotor may be subjected to alternating strains that reduce the expected life of the rotor below a minimum design criteria.

Thus, there exists a need for improved rotors for rotary devices such as turbines and compressors that are used in turbochargers, and for a method of manufacturing such devices. Preferably, the devices should be subjected to reduced strains and stresses, thereby extending the operating lives of the devices, despite cyclic aerodynamic excitation forces, which can occur throughout the

operating range of the device, including at one or more of the vibratory modes of the rotor of the device.

BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWINGS

Having thus described the invention in general terms, reference will now be made to the accompanying drawings, which are not necessarily drawn to scale, and wherein:

Figure 1 is a section view illustrating a rotary apparatus according to one embodiment of the present invention;

Figure 2 is a perspective view illustrating the rotor of the apparatus of Figure 1;

Figure 3 is an elevation view illustrating one of the blades of the rotor of Figure 2 as compared to a conventional blade;

Figure 4A is a graph illustrating a displacement pattern at a first side of a conventional blade corresponding to a second vibrational mode of the blade;

Figure 4B is a graph illustrating a displacement pattern at a second side of the conventional blade of Figure 4A corresponding to the second vibrational mode of the blade;

Figure 5A is a graph illustrating a strain pattern at the first side of the conventional blade of Figure 4A corresponding to the second vibrational mode of the blade;

Figure 5B is a graph illustrating a strain pattern at the second side of the conventional blade of Figure 4A corresponding to the second vibrational mode of the blade;

Figure 6A is a graph illustrating a strain pattern at the first side of the conventional blade of Figure 4A corresponding to a third vibrational mode of the blade;

Figure 6B is a graph illustrating a strain pattern at the second side of the conventional blade of Figure 4A corresponding to a third vibrational mode of the blade;

Figure 7A is a graph illustrating a strain pattern at a first side of the blade of Figure 3 corresponding to a second vibrational mode of the blade according to one embodiment of the present invention;

Figure 7B is a graph illustrating a strain pattern at a second side of the blade of Figure 3 corresponding to a second vibrational mode of the blade;

Figure 8A is a graph illustrating a strain pattern at the first side of the blade of Figure 3 corresponding to a third vibrational mode of the blade;

Figure 8B is a graph illustrating a strain pattern at the second side of the blade of Figure 3 corresponding to a third vibrational mode of the blade; and

Figure 9 is a section view illustrating a rotary apparatus according to another embodiment of the present invention.

DETAILED DESCRIPTION OF THE INVENTION

The present invention now will be described more fully hereinafter with reference to the accompanying drawings, in which some, but not all embodiments of the invention are shown. Indeed, this invention may be embodied in many different forms and should not be construed as limited to the embodiments set forth herein; rather, these embodiments are provided so that this disclosure will satisfy applicable legal requirements. Like numbers refer to like elements throughout.

Referring to Figure 1, there is shown a rotary apparatus **10** according to one embodiment of the present invention. As shown in Figure 1, the rotary apparatus **10** is structured to be a turbine, but in other embodiments of the invention, the rotary apparatus **10** can also be used as a compressor. Compressors and turbines according to the present invention can be included in a turbocharger that is used in conjunction with a combustion engine. Alternatively, the rotary apparatus **10** can be used in other applications, e.g., where operating conditions include cyclically varying pressures.

The rotary apparatus **10** includes a housing **12** that defines an inlet **14** and an outlet **16**. A rotor **30**, which in this case is a turbine wheel, is rotatably

mounted in the housing **12** and configured to rotate with the passage of gas through the housing **12**. Thus, gas enters the inlet **14** flowing in a direction **15** generally tangential to the longitudinal axis of the rotor **30** and a shaft **50**, flows circumferentially in a volute **18** extending circumferentially around the rotor **30**, and then flows generally radially inward through a nozzle **20** to the rotor **30**. The gas exerts pressure on a plurality of radially extending blades **32** on the rotor **30**, thereby turning the rotor **30**. The gas then flows in a generally axial direction **17** out of the outlet **16** of the housing **12**. The rotor **30** is connected to the shaft **50** such that the shaft **50** turns as the rotor **30** is rotated. As used in a turbocharger, the shaft **50** typically extends through a center housing (not shown), where bearings can support the shaft **50** and oil can be provided for lubrication and cooling. Opposite the center housing from the turbine **10**, the shaft **50** can be connected to a compressor wheel (not shown) in a compressor such that the compressor is rotatably operated as the turbine **10** rotates the shaft **50**.

Stators such as vanes **22** or other flow control devices can be provided in the nozzle **20** to control or adjust the flow of the gas therethrough. For example, the vanes **22** can be arranged at circumferential intervals in the nozzle **20** and configured to be rotatably adjusted, thereby varying the geometry of the nozzle **20** and affecting the flow of gas. Such variable nozzles **20** are further described in U.S. Patent No. 6,419,464 to Arnold, the entire content of which is incorporated herein by reference. Alternatively, the vanes **22** can be fixed and an axially sliding piston (not shown) can be used for varying the turbine nozzle flow area. It is appreciated that the adjustment of the nozzle **20** can result in an increase in efficiency of the turbine **10** throughout its range of operation.

The rotor **30** includes a body portion **34**, which is connected to the shaft **50**, and a plurality of the blades **32**, which extend generally radially outward from the body portion **34**. By the term "generally radially" it is meant that the blades **32** do extend radially but may also extend in the axial direction of the rotor **30**. As illustrated in Figures 2 and 3, each blade **32** defines a first edge **36** that extends generally radially and a second edge **38** that extends generally axially. The first

and second edges **36**, **38** are connected by a shroud portion **40** extending therebetween. The edges **36**, **38** are typically configured in close proximity to other portions of the apparatus **10**. For example, the shroud portion **40** of each blade **32** can extend to within less than a millimeter of the housing **12**, and the second edge **38** can extend to within a few millimeters of the vanes **22** of the nozzle **20**.

The second edge **38** of each blade **32** is either a leading or trailing edge of the blade **32**. For example, in the case of a turbine, the second edge **38** of each blade **32** is the leading edge, and the first edge **36** is a trailing edge. That is, as the rotor **30** rotates, the second edge **38** contacts gas flowing into the housing **12**, and the gas thereafter flows toward the first edge **36**. Also, as the rotor **30** rotates, each of the blades **32** passes through a flow field coming off the trailing edge of each of the vanes **22** or other features defined around the circumference of the nozzle **20**. The flow field is nonuniform and unsteady relative to the moving blades **32**. As a result, the pressure on opposite faces **42**, **44** of each blade **32** increases and decreases cyclically. Further, the strain throughout the blades **32** also increases and decreases cyclically at a frequency corresponding to the rotational speed of the rotor **30** and the number and placement of the vanes **22** or other features. Generally, the temporal variation of pressure and strain are not uniform throughout the faces **42**, **44** of the blades **32**.

Variation in the pressure and strain on the blades **32** can also result from other geometric nonuniformities in the housing **12** or from features outside the housing **12** that affect the flow of gas therethrough. For example, gas flowing into the inlet **14** of the apparatus **10** can be supplied through an intake manifold. Bends in the intake manifold can disrupt the flow of the gas therethrough, such that the gas enters the apparatus **10** with a nonuniform pressure over the cross section of the inlet **14**.

Preferably, the second edge **38** of each blade **32** defines a nonlinear profile as projected in the meridional (radial-axial or R-Z) plane. That is, the profile of the second edge **38**, as projected in the R-Z plane, is not straight. The nonlinear

second edge **38** can include one or more linear portions, but at least part of the edge **38** is nonlinear in the R-Z plane, e.g., including a nonlinearity such as a curved portion or an angle or other discontinuity as projected in the R-Z plane. For example, Figure 3 graphically illustrates the outer shape, or profile, of the blade **32** according to one embodiment of the present invention. The axes shown in Figures 3-8 correspond to the R, or radial, direction and the Z, or axial, direction of the rotor **30**. As illustrated in Figure 3, the profile of the second edge **38** is nonlinear as projected in the R-Z plane. More particularly, the second edge **38** defines a profile in the R-Z plane that is concave such that the curvature of the concave portion defines a center of curvature located radially outward of the second edge **38**. In contrast, the linear profile of a second edge **38a** of a conventional turbine rotor blade **32a** is shown in dashed line. Advantageously, the nonlinear configuration of the second edge **38** can reduce the strain that is induced in the blade **32** due to the cyclic aerodynamic excitation forces on the blade **32**. Preferably, all of the blades **32** of the rotor **30** have second edges **38** that are substantially similar in profile.

According to one embodiment of the present invention, the configuration of the blade **32** is determined by first determining the unsteady pressure on the blade **32** associated with operation and the resulting displacement and strain of the blade **32**. The term "displacement" refers generally to the displacement of the blade **32** that occurs in the direction of the unsteady pressure forces on the blade **32**. The profile of the blade **32** is then modified to reduce a portion of the blade **32** that is exposed to unsteady high pressure and a high displacement occurring in the direction of the unsteady pressure. For example, the configuration of the blade **32** illustrated in Figure 3 can be developed by first providing first parameters that dimensionally define a blade, such as the conventional blade **32a** with the linear second edge **38a** as shown in Figures 4A and 4B. In addition, the first parameters can define the material or other physical characteristics of the blade **32a** such as the strength or stiffness of the blades **32a**. Second parameters defining an expected cyclic pressure contour for the conventional blade **32a** are also provided.

The second parameters can define the frequency and amplitude of a cyclic pressure exerted on opposite faces **42a, 44a** of the blade **32a** as the blade **32a** is rotated in a housing, e.g., due to the presence of vanes or other features proximate to the blade **32a**. In particular, the second parameters can define a temporal pressure variation that is nonuniform over a contour, i.e., a distribution of unsteady pressure over each face **42a**, **44a** of the blade **32a**, which results when the blade **32a** is rotated at a speed such that the cyclic force occurs at a frequency corresponding to the second vibrational mode of the blade **32a**. A resulting displacement contour or pattern of the blade **32a**, i.e., defining the displacement throughout the blade **32a** that results from the cyclic pressure, can also be determined. Similarly, a strain contour can be determined to define the strain throughout the blade **32a** that results from the cyclic pressure. The pressure, displacement, and strain contours can be determined mathematically, e.g., using a computer program for mathematically modeling the pressure, displacement, and strain according to the first and second parameters. Alternatively, the pressure, displacement, strain, and/or stress on the blades **32a** can be determined empirically or by other methods.

The displacement and strain contours for each face **42a**, **44a** of the conventional blade **32a** are graphically illustrated in Figures 4A, 4B and 5A, 5B, respectively. As shown in Figures 4A, 4B, 5A, and 5B, the maximum displacements and strains for the illustrated embodiment generally occur near the second edge **38a** of the blade **32a**, i.e., the leading edge for a turbine blade. It can be seen in Figures 4A and 4B that a portion **46a** near the center of the second edge **38a** is subjected to a displacement that is relatively higher than the adjacent portions of the blade **32a**. As shown in Figure 5A, the strain occurring at the same portion **46a** of the blade **32a** is also relatively higher than the strain at the adjacent portions of the blade **32a**. Typically, the portions of the blade **32a** subject to high strain or displacement coincide at least partially with those portions of the blade **32a** that are subject to high cyclic pressures.

According to one embodiment of the present invention, the configuration of the blade **32** is modified by adjusting the first parameters that geometrically define the conventional blade **32a**. More particularly, the first parameters are adjusted to define a nonlinear edge and at least partially remove the portion **46a** that is subjected to relatively higher displacement than adjacent portions. Thus, the blade **32** illustrated in Figure 3 has been modified to exclude at least part of the conventional blade **32a** that is subjected to relatively high displacements. Preferably, the blade **32** can be modified to exclude portions of the conventional blade **32a** where high displacement coincides with high cyclic pressures, i.e., where the blade **32** is being significantly displaced in the direction of the unsteady cyclic pressure. Advantageously, the modification of the profile of the blade **32** can reduce the strain and stress of the blade **32**. For example, Figures 7A and 7B illustrate the strain contour of the blade **32** operating at similar operational parameters as the conventional blade **32a**. The maximum strain on the blade **32** is significantly less than that of the conventional blade **32a** shown in Figures 5A and 5B. More particularly, the highest strains that occur at the second edge **38a** of the conventional blade **32a** have been eliminated. Further, the strains near the nonlinear edge **38** of the blade **32** of the present invention are less than the strains that occur in the corresponding portions of the conventional blade **32a**.

While the present invention is not limited to any particular theory of operation, it is believed that the change in the profile of the blade **32** can result in a change in the mode shape of the rotor **30** to reduce the displacements or strains that result from exciting a particular mode of the rotor **30** with the excitation forces that occur. That is, it is believed that the change of the shape of the blade **32** results in a corresponding change in the mode shape, thereby making the rotor **30** less affected by the excitation forces.

While Figures 7A and 7B illustrate the reduction in strain associated with a cyclic force that occurs at a frequency for exciting the blades **32** at the second vibrational mode of the blade **32**, it is also appreciated that the nonlinear profile of the blade **32** can also result in a decrease in the strain that occurs in the blade **32**

during other modes of operation. For example, Figure 6A and 6B illustrate the strain contour of the conventional blade **32a** during operation at a speed that induces the cyclic force at a frequency corresponding to the third vibrational mode of the blade **32a**. Similarly, Figures 8A and 8B illustrate the strain contour of the blade **32** of the present invention for a cyclic force that corresponds to the third vibrational mode of the blade **32**. As illustrated, the strain at the nonlinear edge **38** of the blade **32** is less than the strain at the linear edge **38a** of the conventional blade **32a**.

The adjustment of the profile of the second edge **38** need not conform precisely to the portion **46a** of the blade **32a** that is subjected to relatively high displacements. Instead, the adjustment of the profile can also be determined in consideration of the strength of the blade **32**, the ease of casting or otherwise forming the blade **32**, the aerodynamic performance of the blade **32** and, hence, the rotor **30**, and additional considerations. For example, the profile can define a smooth curve in order to minimize sharp edges that might otherwise concentrate stress and/or induce unnecessary pressure losses. The change in the profile of the edge **38** can also result in a reduction in the vibrating mass of the rotor **30**, which typically increases the natural vibratory frequencies of the rotor **30**, possibly increasing one or more of the resonant frequencies of the rotor **30** beyond the operating frequency of the rotor **30**.

In addition, the adjustment or modification of the profile of the blades **32** can be performed iteratively, e.g., by repeatedly determining the displacement and/or strain profile of the blades **32** and modifying the blades **32** to exclude one or more portions subjected to the highest displacements.

While the foregoing discussion has described the rotor **30** in the context of a turbine wheel for a turbine, it is also appreciated that the rotor **30** can instead be used for other applications. For example, as shown in Figure 9, the rotor **30** can be a compressor wheel, and the housing **12** can be a compressor housing for a compressor **60**. During operation of a compressor **60**, the compressor wheel **30** can be subjected to pressures, displacements, and strains that are similar to those

that occur in the turbine wheel. In particular, the compressor wheel **30** can be subjected to cyclic forces, e.g., as a result of the blades **32** rotating in close proximity to a stator such as a vane **22**. Typically, when used in a compressor, the first edge **36** of each blade **32** is the leading edge and the second edge **38** is the trailing edge. Thus, air or other gas flows through the housing **12** in the opposite direction from that which is described above, i.e., the air enters axially in a direction **15a** through inlet **14a** toward the first edge **36** of the blades **32**, is pressurized by the blades **32**, and delivered radially outward therefrom to the volute **18**. From the volute **18**, the compressed air is discharged through outlet **16a** in a transverse direction **17a**. In the context of a compressor, the portion of the housing **12** between the rotor **30** and the volute **18** is generally referred to as a diffuser **21**, in which the air from the compressor slows in velocity. The vanes **22**, which can be adjustable, can be provided in the diffuser **21** to control the flow of the air therethrough. The vanes **22** can be configured in close proximity to the rotor **30** such that the vanes **22** induce a cyclic change in pressure on the blades **32** of the rotor **20** as the rotor **30** rotates, thereby subjecting the blades **32** to a cyclic aerodynamic excitation force. The displacement and/or strain on the blades **32** can be modeled as described above, and the second edge **38** of the blades **32** can be provided with a nonlinear profile to minimize the strain in the blades **32**.

In some embodiments of the present invention, the first edge **36** of the blades **32** can also define a nonlinear contour to minimize strains at and proximate to the first edge **36**. For example, contouring of the first edges **36** of the blades **32** can be advantageous where the rotor **30** is subjected to cyclic pressure variations at the first edge **36**. Such variations at the first edge **36** can be caused, e.g., by inlet guide vanes (not shown), by geometric nonuniformities in the housing proximate to the first edges **36**, or by features outside the housing that result in nonuniform flow through the housing **12**.

Many modifications and other embodiments of the invention set forth herein will come to mind to one skilled in the art to which this invention pertains having the benefit of the teachings presented in the foregoing descriptions and the

associated drawings. Therefore, it is to be understood that the invention is not to be limited to the specific embodiments disclosed and that modifications and other embodiments are intended to be included within the scope of the appended claims. Although specific terms are employed herein, they are used in a generic and descriptive sense only and not for purposes of limitation.